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EXPERIMENTAL INVESTIGATION OF AERODYNAMIC DRAG IN TREE CROWNS EXPOSED TO STEADY WIND (CONIFERS).

A Phase Report
by

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under direction of
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SUMMARY

Shock-wave winds which follow atomic explosions transmit force to trees by aerodynamic drag. The first step in evaulation of these drag forces and their associated effects on trees is the determination of aerodynamic drag of tree crowns exposed to steady wind. These drag data then must be correlated with pertinent physical characteristics of tree crowns to allow extrapolation to all tree sizes and shapes as well as to other species. If these same data can be associated with drag caused by impulsive wind loading, they form an integral step in the determination of circumstances under which tree breakage and uprooting occur.

This report describes laboratory and field work and subsequent analysis which determine drag forces present in coniferous tree crowns exposed to steady wind.

Crowns of saplings approximately one inch d.i.b.[1] were exposed in a wind tunnel to wind velocities which ranged from 30 to 95 feet per second. Tree crowns with stems between three and seven inches d.i.b. (saplings and poles) were mounted on a truck bed and exposed to wind velocities between 35 and 75 feet per second. In both cases drag and bending moment were determined as a function of velocity. Following each test, the tree stem and crown were measured and analyzed.

1/ Stem diameter inside bark at the base of the crown.

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Variation in tree crown drag has been found to be due primarily to bending which results from the application of drag force. Drag data and tree analysis data for the trees tested are correlated in non-dimensional form for each species tested. The crown drag per unit weight of dry crown is shown as a function of the bending moment at the base of crown divided by the dynamic pressure for any given crown geometry. These relationships are different for each species tested; however, their general characteristics are the same.

These results enable the determination of crown drag over a range of wind velocity sufficiently high to cause tree breakage or uprooting under steady wind. Application of these results to impulsive wind loading requires considerable extrapolation. Recommendations are made to employ higher and lower wind tunnel velocities to verify further the relationships presented and in a water channel to investigate the role of Reynolds modulus in tree crown drag.

EXPERIMENTAL PROCEDURE

Wind-tunnel Drag Tests

Foliage, branch, and stem drag as well as crown drag of conifer saplings were tested[2] in the University of California three-foot by three-foot low-velocity, open throat wind tunnel located on the Berkeley campus. Test specimens were stored at 40° F with their butt ends in water. They were then mounted in an inverted position in the tunnel with their butt ends clamped to the moment sting. Tare drag and moment determinations were made and the balances calibrated. Oven-dry weights of stems, foliage, and branches were determined after the tests were completed.

Drag and moment forces were measured with dead weight pan balances to the nearest two grams pan weight, which corresponds to 0.02 lb drag force.

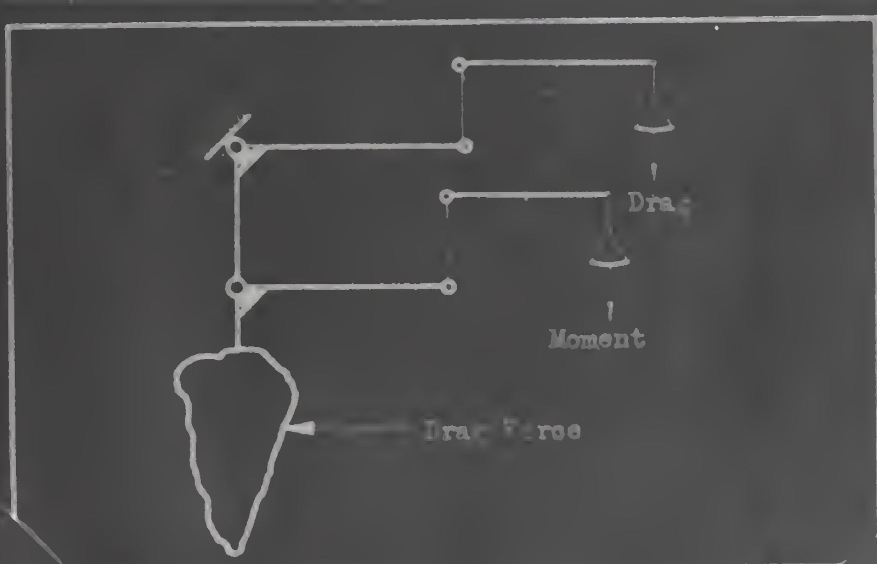

Figure 1. Schematic Diagram of the Drag-moment Balance

2/ Tests were made during June 1951.

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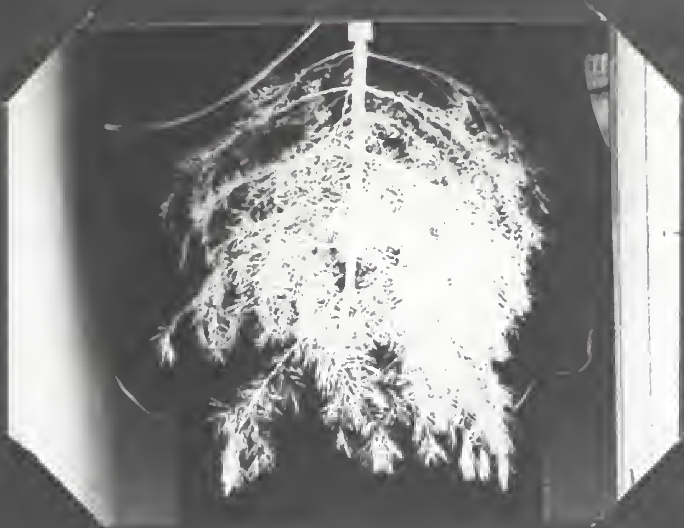

Figure 2. White Fir (WT2) Exposed at Zero Wind Velocity

Figure 3. White Fir (WT2) Exposed at 28.1 fps in Wind Tunnel

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Figure 4. White Fir (WT2) Exposed at 66.5 fps in Wind Tunnel

Measurements of velocity were made at the center line of the tunnel at a position forward of the sapling using a Prandtl-type Pitot tube and inclined Ellison gage. Readings were made to the nearest 0.01 inch of water.

Validity of mounting saplings in an inverted position rather than upright was confirmed by running comparison tests both ways with white fir (WT2) (see Figure 8).

Moving Vehicle Drag Tests

Crown drag tests on larger trees were made during August, 1951 at the Mount Shasta Branch of the California Forest and Range Experiment Station. Tree crowns selected from rather open mixed conifer stands on the basis of crown form and symmetry were cut in the

afternoon and mounted on the bed of a one and one-half-ton truck. Early the next morning test runs were made when natural wind velocity was less than three miles per hour.

Straight sections along State Highway 89 east of McCloud, California, provided suitable test courses about 2,000 feet long. Truck speed was held constant while runs were made in both directions to cancel effects of natural winds, and average truck velocity was computed from stop watch times and known distances.

The base of the tree stem rested on a plate which was mounted on rollers. Two collars fixed to the tree stem, one at its base and one five and one-half feet above the base, were attached to dynamometers in such a way that the difference in forces measured by the dynamometers equalled drag while the lower dynamometer measured the moment about the upper moment center.

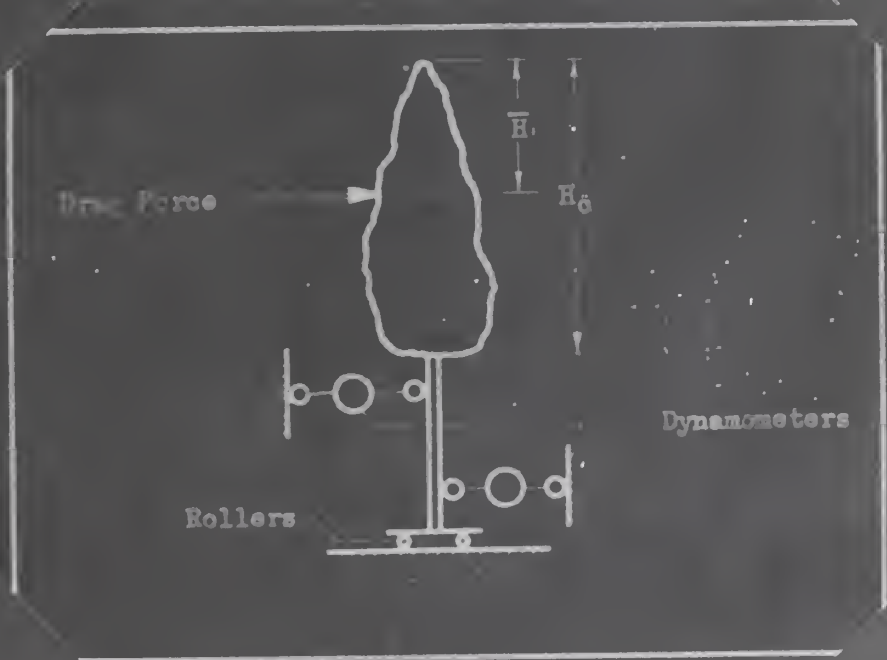

Figure 5. Schematic Diagram of the Drag-Force Measuring System Mounted on Truck Bed

Each dynamometer consists of four SR4 type A-5 strain gages mounted on a 64 ST aluminum ring. As the ring deflected under load, the resultant strain caused a change in the resistance in the gages, which in turn was recorded on a Foxboro SR4 circular chart recorder. Dynamometer calibrations made on a calibrated tensile testing machine before and after the tests agreed within two percent. The least count on the recorder corresponded to ten pounds dynamometer load.

Figure 6. Dynamometers

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Arrangement of the gages as shown in Figure 7 allows only tensile loading to be recorded. Adjacent gages mounted on opposite legs of the bridge circuit subtract algebraically, hence any strain produced by bending or torsion is cancelled.

Figure 7. Dynamometer Wiring Diagram

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When drag and moment forces had been measured for the full crown of each tree, the lower branches were removed and the runs repeated with the top half of the crown intact. These latter values were then corrected for exposed stem drag assuming that the stem acted as a cylinder of diameter equal to the mean stem diameter.

Full Crown　　Half Crown

Figure 8. White Fir (WT8) Mounted on Truck

Drag on one section of stem between dynamometers was measured. Due to shielding by the truck cab, forces exerted on this section at maximum velocity were found to be negligible.

Green weight and current moisture content of stem, branches, and foliage were measured immediately after each test, from which data dry weights were obtained. Ponderosa pine foliage-branch ratios were determined from previously measured values. For the other species this measurement was made on the crowns tested.

Several difficulties had to be overcome before these field tests could be made successfully. All leads had to be shielded and grounded to the truck chasis. Roughness of the road surface made it impossible to obtain suitable power from two six-volt wet storage batteries through a 12-volt DC-110 volt AC synchronous converter. This trouble was overcome by using a 110 volt AC generator set. Truck vibration also made it necessary to bolt the recorder solidly to the truck frame. Even more serious, vertical vibrations of the truck on the roadbed caused small light-weight crowns to lift off the roller to give erroneous measurements of drag and moment.

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RESULTS

Physical characteristics of sapling and pole crowns which were tested are described in Tables I and II.

Figure 9 shows the variation of crown drag with velocity for white fir sapling WT2. Data taken in the upright position (two velocities only) check closely with that taken in the inverted position. Rotation through 180 degrees to expose a fuller crown on one side also does not change the results appreciably.

Figures 10 through 15 show the correlated data for each species tested. The crown drag <u>includes</u> the drag of the associated stem but does not include the drag of any exposed stem below the crown base. To correct measured values the exposed stem was assumed to act as a cylinder with a drag coefficient of 1.20 and a diameter equal to the mean exposed stem diameter. The drag coefficient is probably slightly low due to the roughness of the stem; however, the maximum correction was of the order of five percent. Variations between species are shown graphically in Figure 16.

The center-of-pressure measurements were averaged for each full and half crown since no consistent variation with velocity was found. The center-of-pressure measurements reported for the saplings were those found at the lowest velocity tested. At higher velocities the center of pressure moved toward the crown base due to the bending of the stem. These data are shown in Figure 17 for each species tested in comparison with the center of mass of the foliage. The variation in position of the center of pressure of the saplings with increased velocity is shown in Figure 18.

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TABLE I

PHYSICAL CHARACTERISTICS OF SAPLINGS TESTED IN WIND TUNNEL

Number	Species	Height of Crown, H_c	Diameter at Base of Crown, d_c	H_c/d_c	Dry Weights: Crown, W_{dc}	Dry Weights: Branch divided by foliage, W_{db}/W_{df}
		inches	inches	dimensionless	pounds	
WT7	Ponderosa pine (Pinus ponderosa)	28	0.993	28.2	0.322	0.60
WT8	ditto	27	0.917	29.5	0.361	0.49
WT10A	Sugar pine (P. lambertiara)	28.75	0.775	37.1	0.366	0.32
WT9	Douglas fir (Psdudotsuga taxifolia)	25	0.65	38.5	0.355	0.39
WT12	ditto	25.5	0.618	41.3	0.326	0.39
WT2	White fir (Abies concolor)	19.5	0.740	26.3	0.558	0.41
WT11	ditto	23	0.658	35.0	0.418	0.30
WT11A	ditto	28	0.775	36.1	0.595	0.30 1/
WT14	ditto	27	0.748	36.1	0.368	0.30 1/
WT10	Incense cedar (Libocedrus decurrens)	21.5	0.751	28.4	0.312	0.32
WT12A	ditto	29	0.895	32.4	0.464	0.32 1/

1/ Estimated from similar saplings

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TABLE II
PHYSICAL CHARACTERISTICS OF TREE CROWNS TESTED

Number	Species	Height of Crown, H_c	Diameter at Base of Crown, d_c	H_c/d_c	Dry Weights: Crown W_{dc}	Dry Weights: Branch divided by foliage, W_{db}/W_{df}
		feet	inches	dimensionless	pounds	
VT2F[1]	Ponderosa pine (Pinus ponderosa)	20	6-3/4	35.6	103	1.55[2]
VT2H[1]	ditto	14	5	33.6	48.2	1.15[2]
VT3F	ditto	19.4	7-1/4	32.1	89.1	1.65[2]
VT3H	ditto	12.4	5	29.8	44.3	1.15[2]
VT4F	ditto	14.6	5-3/8	32.5	66.1	1.20[2]
VT4H	ditto	10.2	3-7/8	31.5	27.4	0.85[2]
VT5F	ditto	16.1	4-5/8	41.7	48.4	1.06[2]
VT10F	Sugar pine (Pinus lambertiana)	15.7	5-3/8	35.0	33.1	0.799
VT10H	ditto	9.1	3-1/4	33.5	11.1	0.724
VT9F	Lodgepole pine (Pinus contorta)	17.1	6	34.2	58.2	2.60
VT9H	ditto	10.1	3-3/4	32.2	22.5	1.56
VT13F	ditto	16.9	5-3/8	37.7	42.8	1.38
VT13H	ditto	11.9	4-1/4	33.6	17.6	0.885
VT14F	Douglas fir (Pseudotsuga taxifolia)	17.1	4-3/8	36.0	44.6	0.915
VT14H	ditto	11.8	3-1/8	37.6	16.4	0.842
VT15F	ditto	15.2	3-3/4	48.5	27.9	0.85
VT15H	ditto	11.2	2-3/4	48.7	10.6	0.70
VT7F	White fir (Abies concolor)	17.0	5-1/4	38.8	50.8	0.688
VT7H	ditto	12.0	3-3/4	38.4	26.5	0.540
VT8F	ditto	15.4	5-1/2	33.6	69.6	0.807
VT8H	ditto	10.5	4-1/4	29.7	32.3	0.623

1/ F - tree tested with full crown; H - tree tested with half crown.
2/ Estimated -- based on "Stem and crown characteristics of several coniferous species", report in preparation by personnel of U. S. Forest Service Division of Fire Research.

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TABLE II (con't.)
PHYSICAL CHARACTERISTICS OF TREE CROWNS TESTED

Number	Species	Height of Crown, H_c	Diameter at Base of Crown, d_c	H_c/d_c	Dry Weights: Crown, W_{dc}	Dry Weights: Branch divided by foliage, W_{db}/W_{df}
		feet	inches	dimensionless	pounds	
VT11F 1/	Incense cedar (Libocedrus decurrens)	14.1	3-5/8	50.0	24.1	0.697
VT11H 1/	ditto	8.7	2-1/4	46.2	9.5	0.583
VT12F	ditto	16.3	6-1/4	31.2	61.3	0.707
VT12H	ditto	9.8	3-5/8	32.5	20.8	0.588

1/ F - tree tested with full crown; H - tree tested with half crown.

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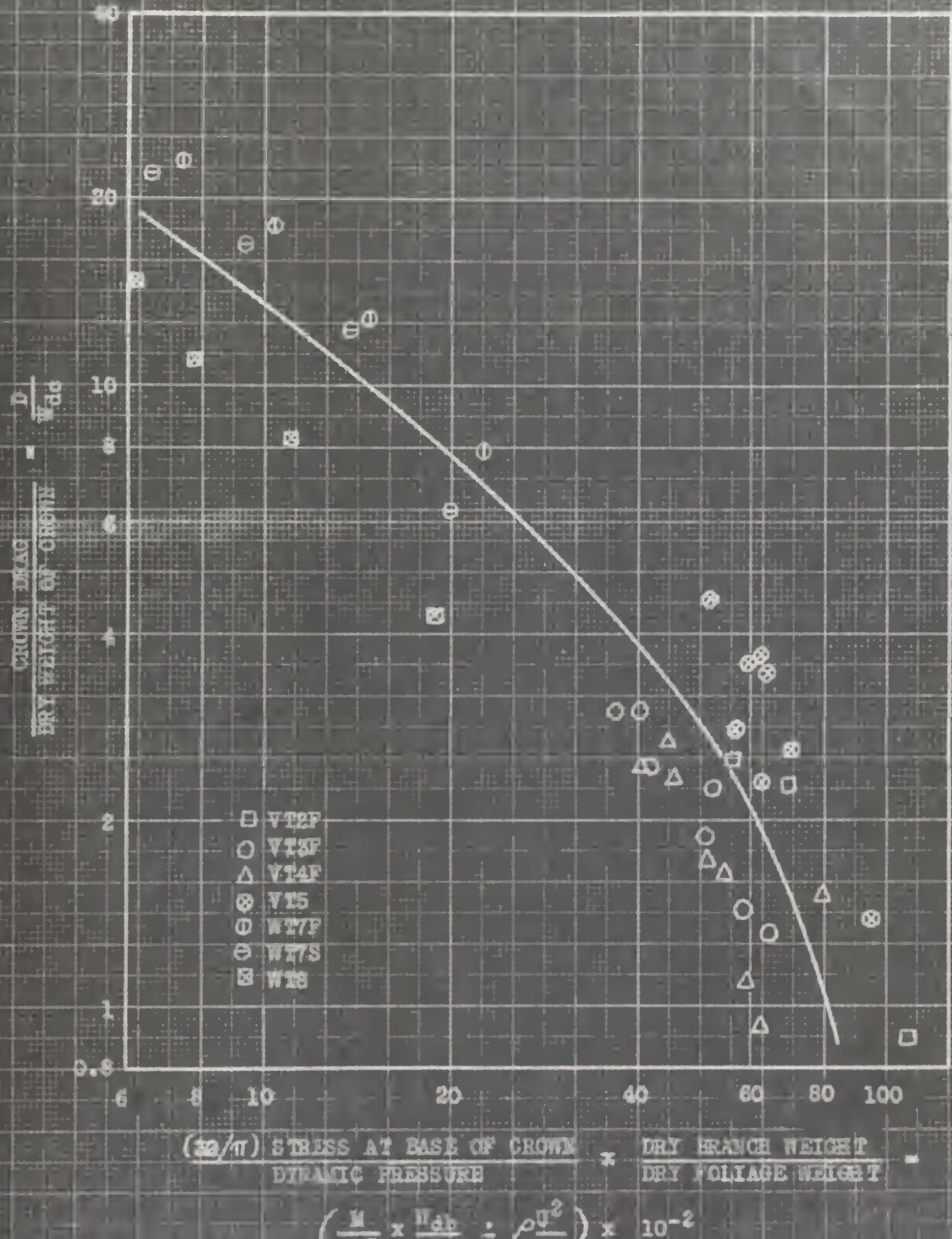

Figure 10. Dimensionless Correlation of Aerodynamic Drag Data — Ponderosa Pine Crowns

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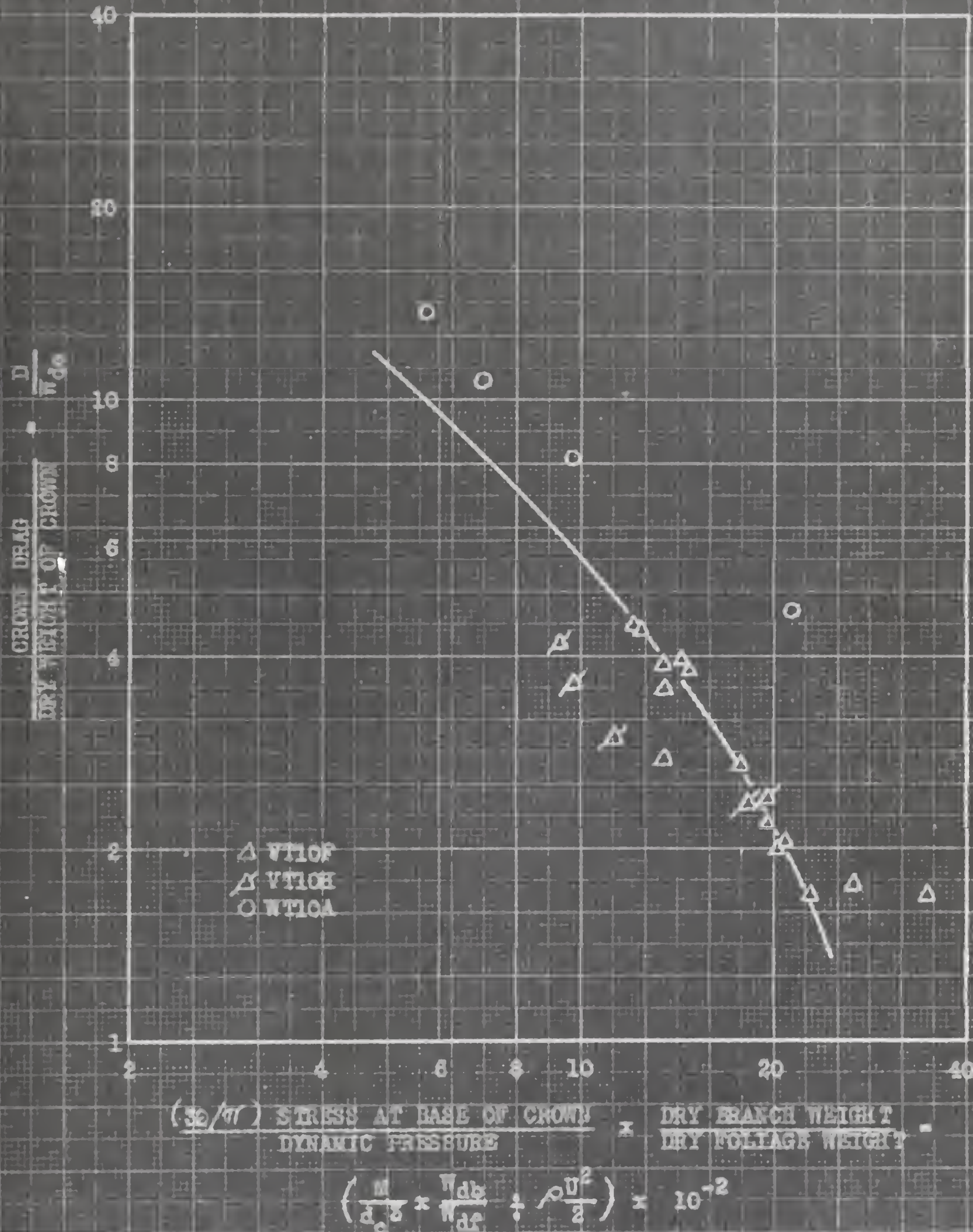

Figure 11. Dimensionless Correlation of Aerodynamic Drag Data — Sugar Pine Crowns

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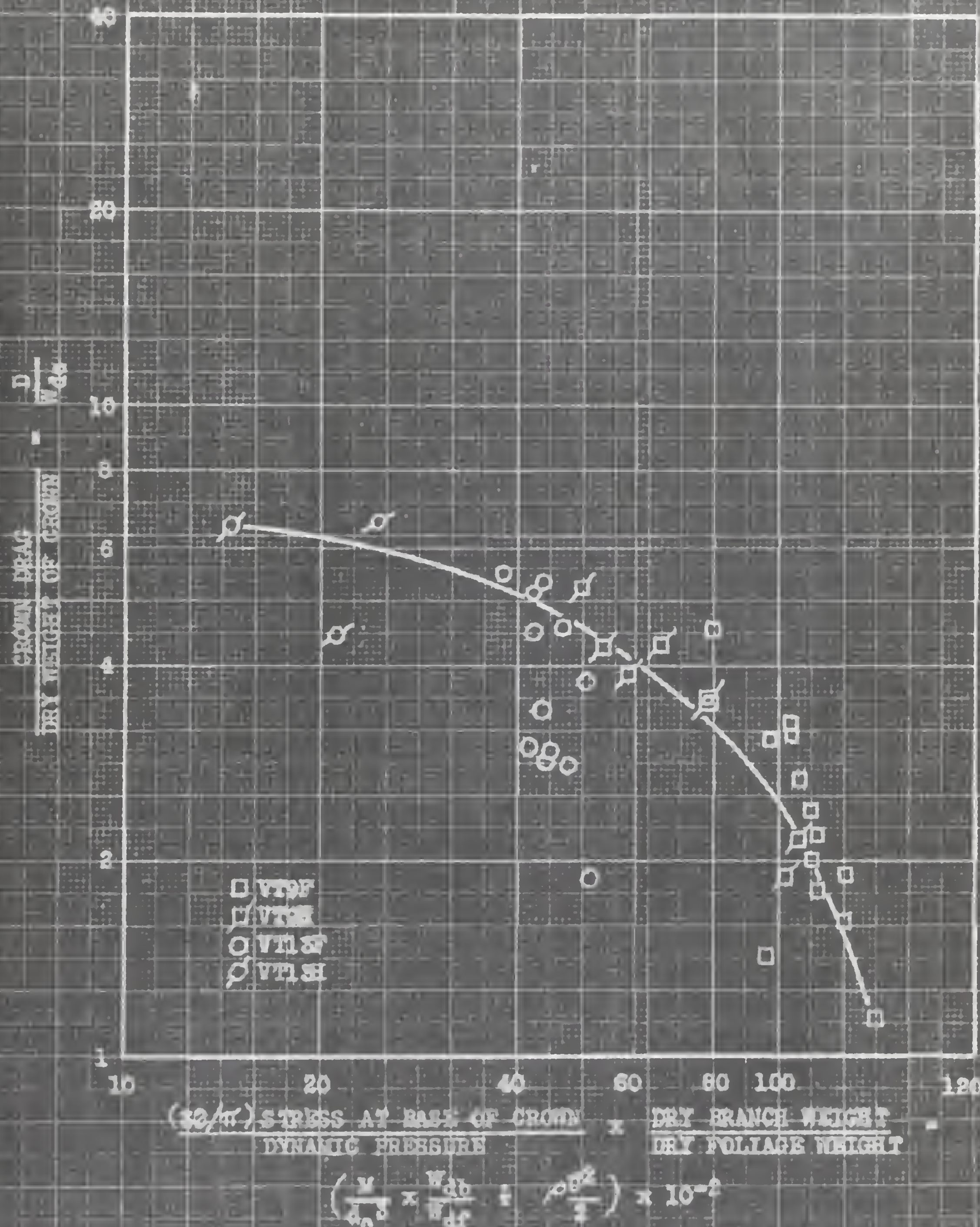

Figure 12. Dimensionless Correlation of Aerodynamic Drag Data — Lodgepole Pine Crowns

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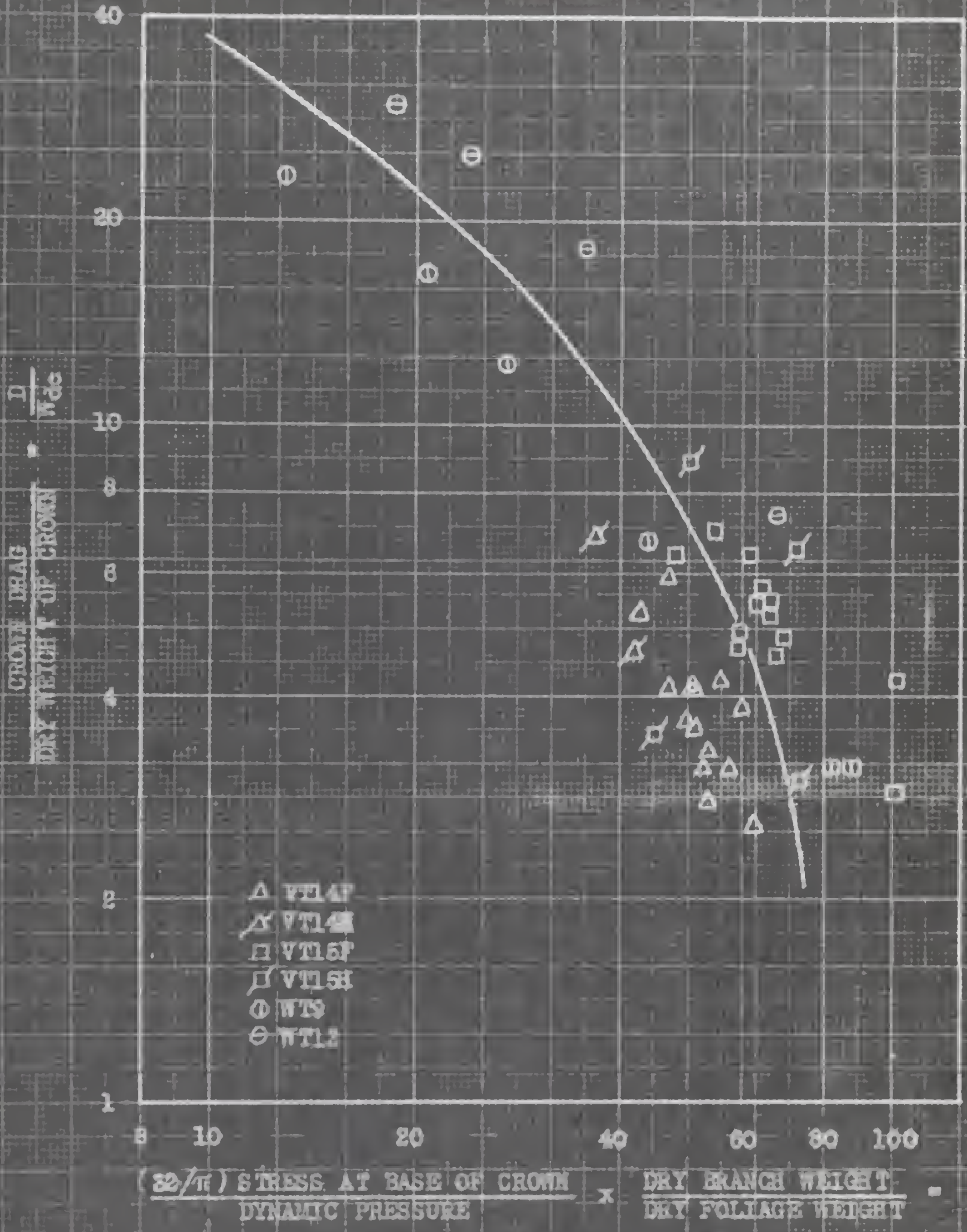

Figure 15. Dimensionless Correlation of Aerodynamic Drag Data — Douglas Fir Crowns

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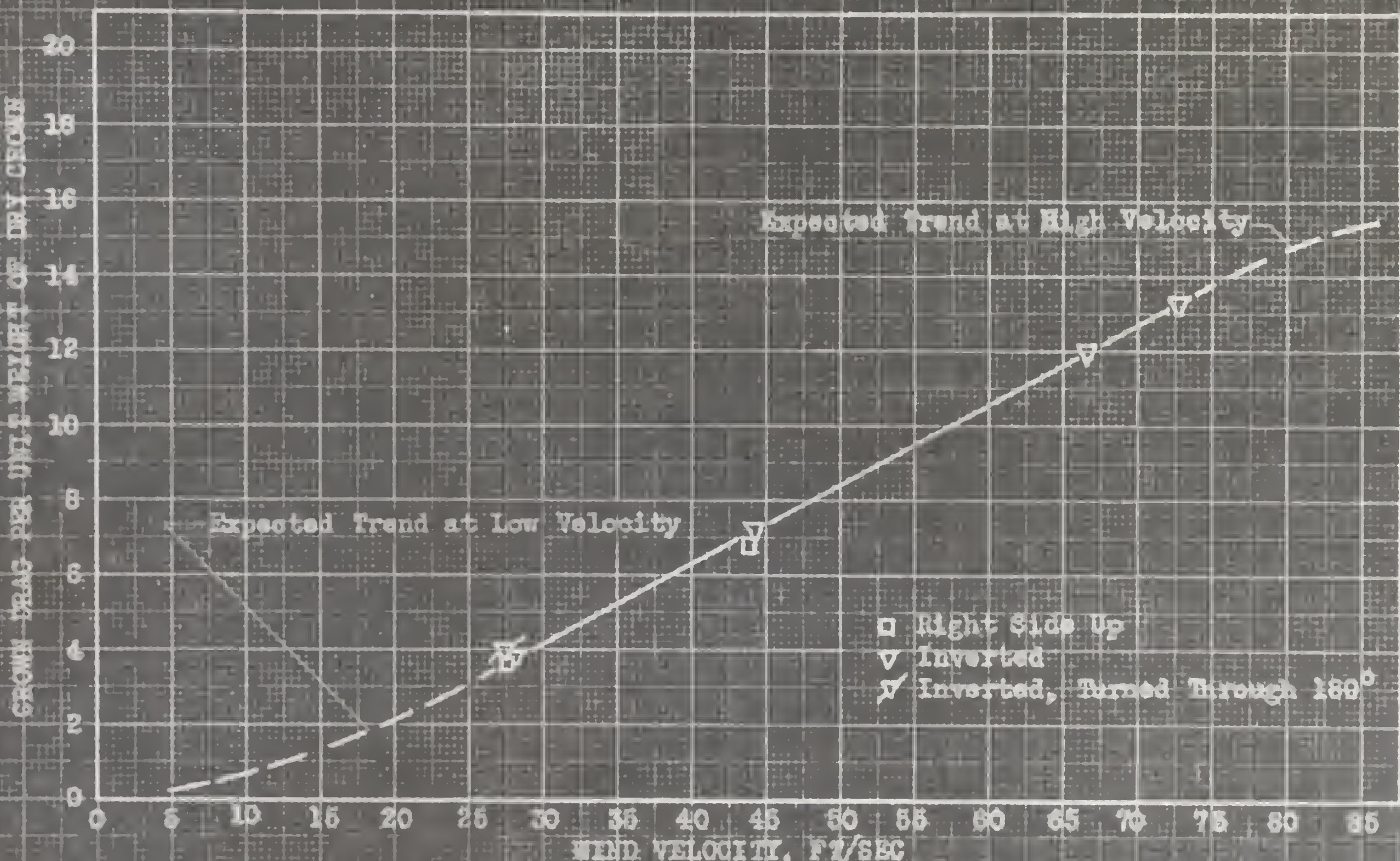

Figure 9. Drag-velocity Relationships for White Fir Sapling (WF2)

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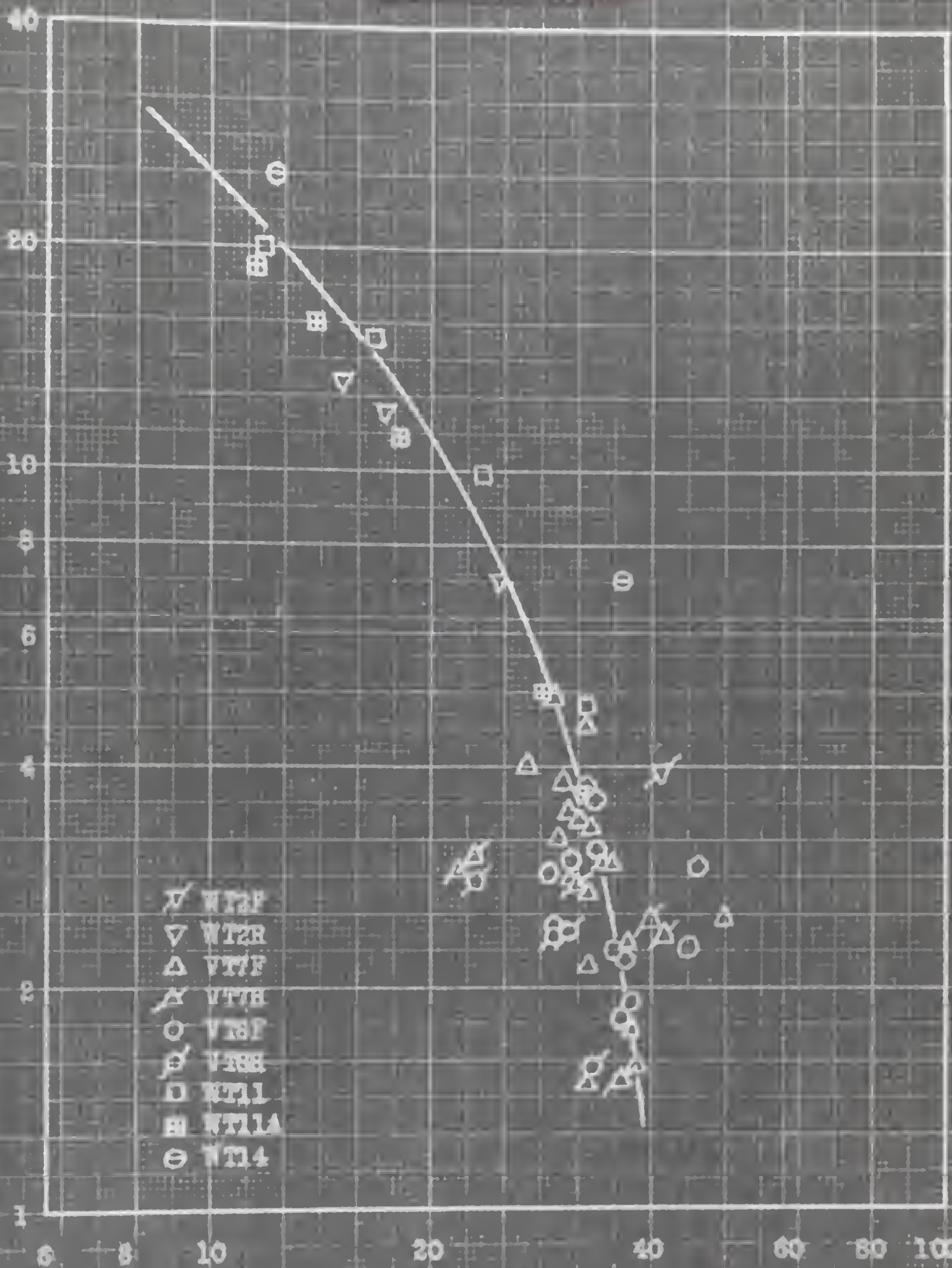

(M/W) STRESS AT BASE OF CROWN / DYNAMIC PRESSURE x DRY BRANCH WEIGHT / DRY FOLIAGE WEIGHT =

$$\left(\frac{M}{Z_s} \times \frac{W_{db}}{W_{df}} \div \rho\frac{U^2}{2}\right) \times 10^{-2}$$

Figure 14. Dimensionless Correlation of Aerodynamic Drag Data — White Fir Crowns

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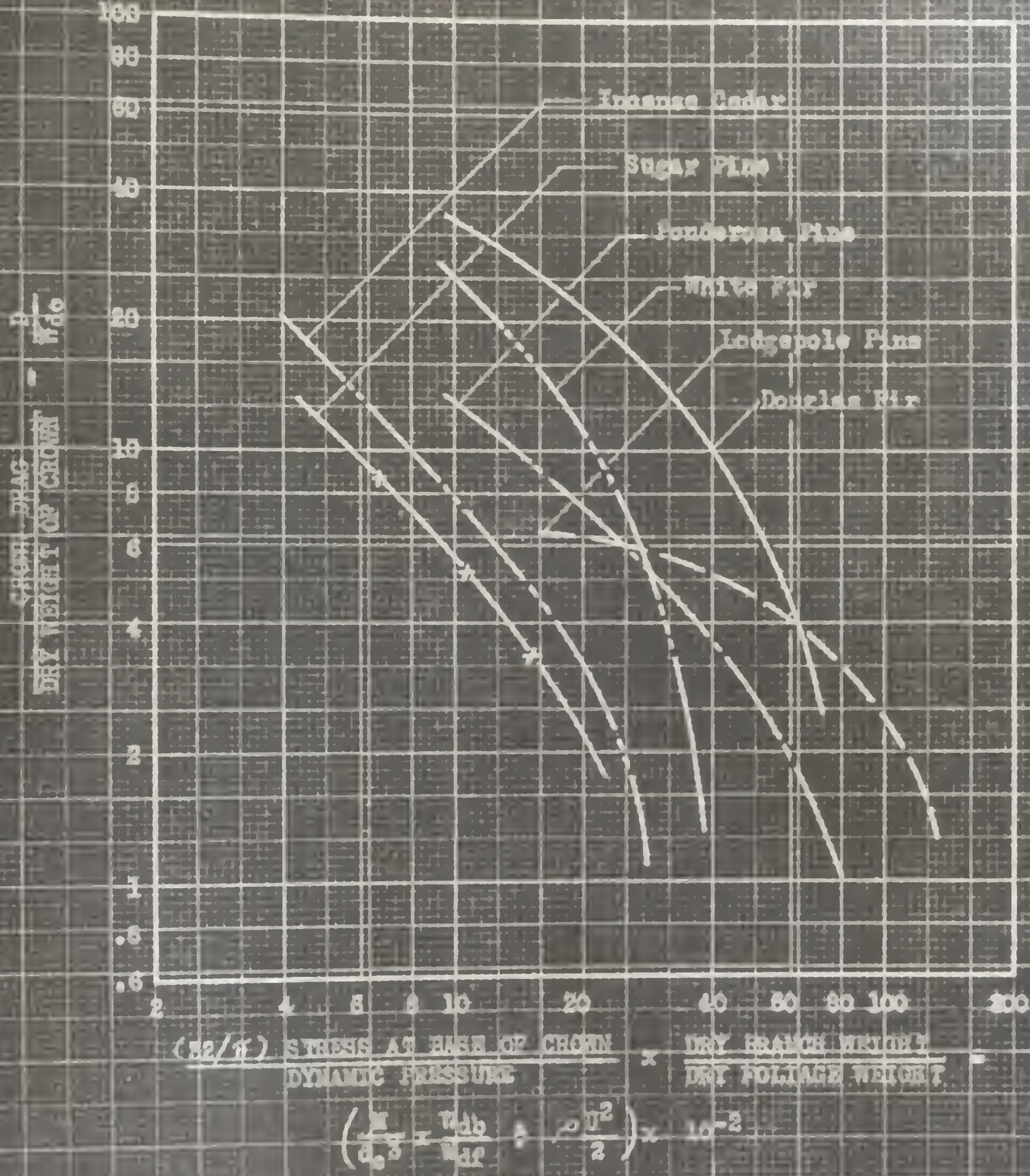

Figure 16. Dimensionless Correlation of Aerodynamic Drag Data — All Species Tested

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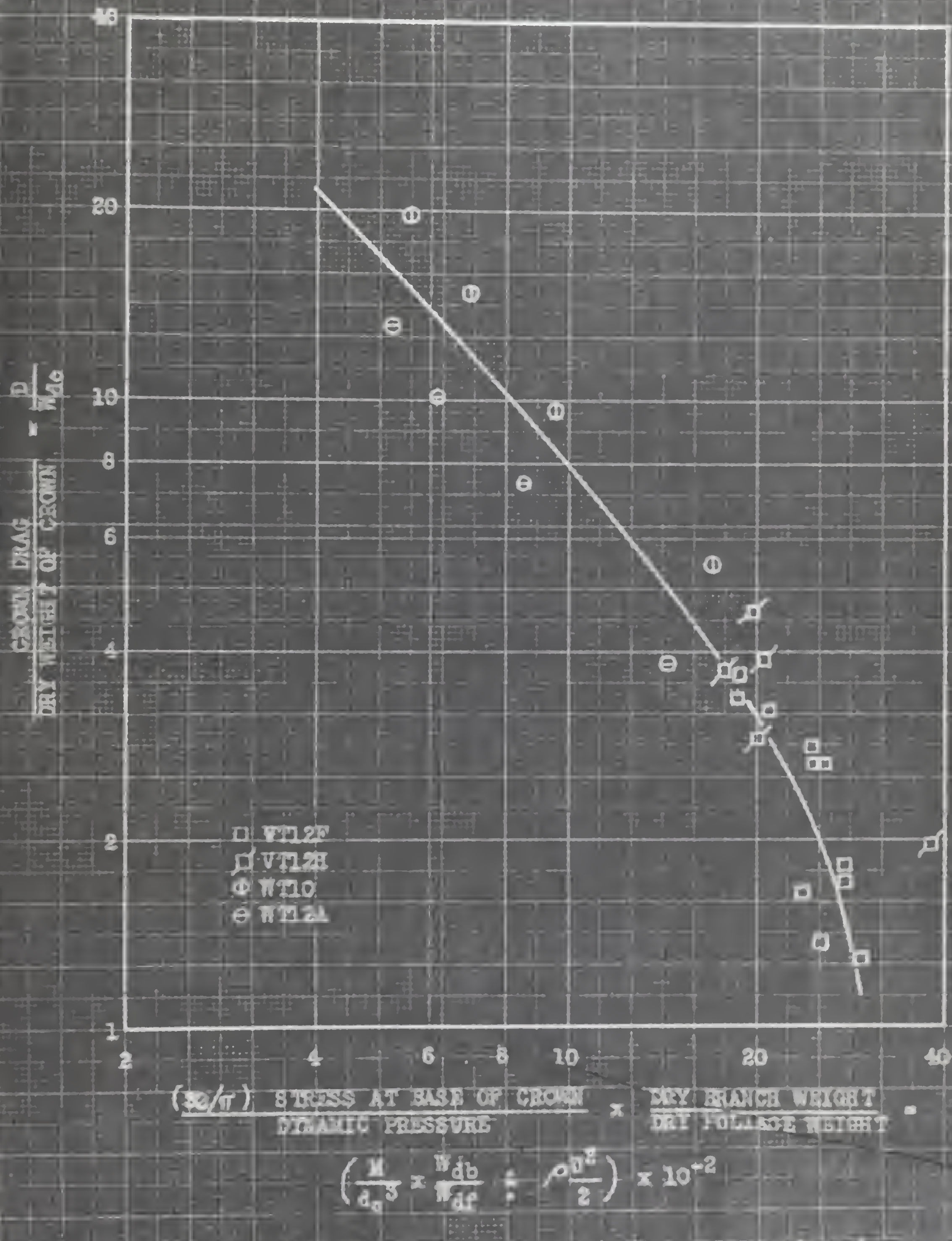

Figure 15. Dimensionless Correlation of Aerodynamic Drag Data - Incense Cedar Crowns

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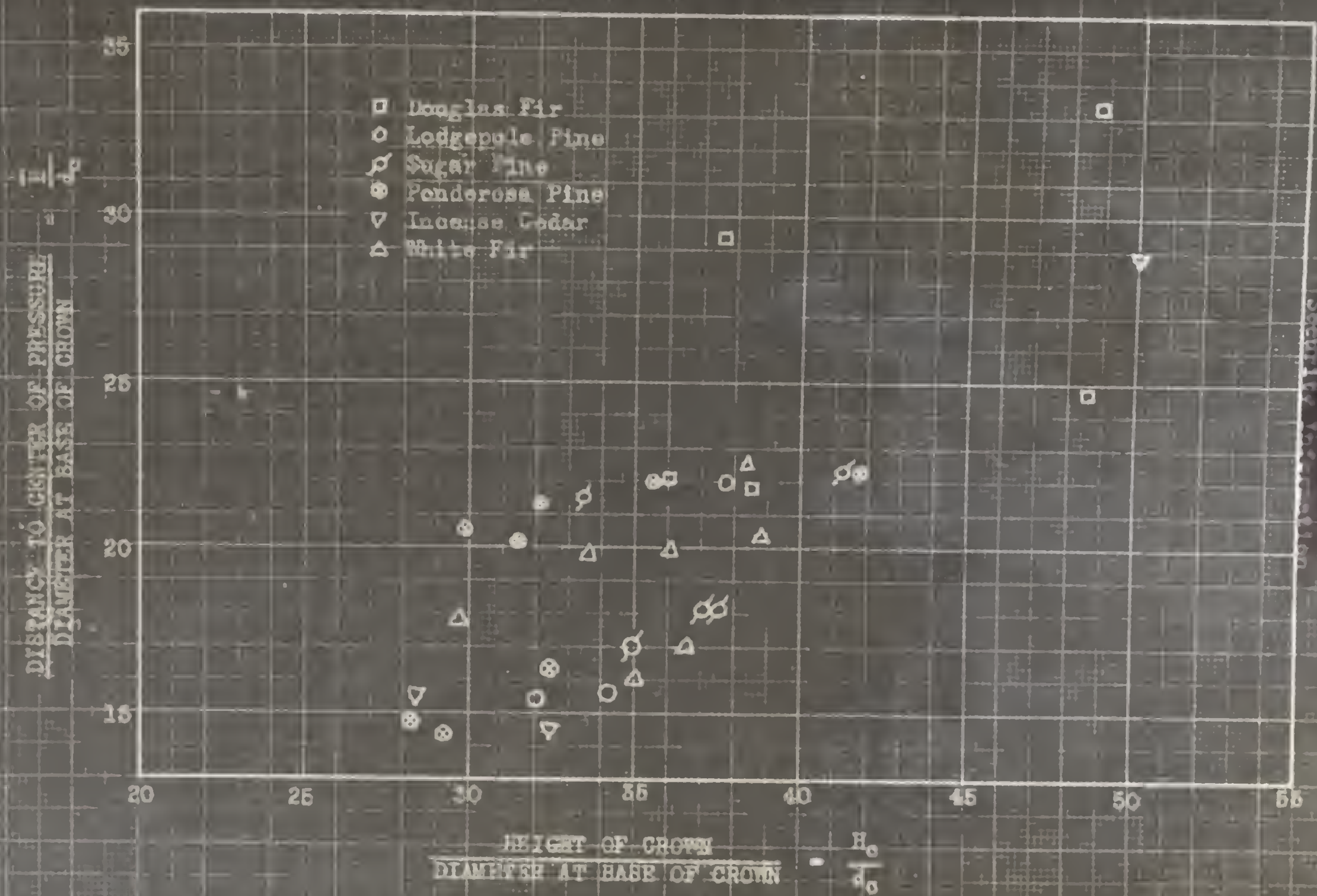

Figure 17. Location of Center of Pressure of Aerodynamic Drag

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DISCUSSION

As is characteristic with all bodies in submerged flow, drag force of tree crowns is proportional to dynamic pressure and area upon which it acts. This proportionality factor (drag coefficient) is not always constant but depends on the mechanism which brings about drag. For rigid bodies the drag mechanism can be characterized in terms of a Reynolds modulus based on some characteristic dimension. However, non-rigid bodies (tree crowns) tend to deform under drag loading. The drag coefficient then is dependent on method and amount of deformation. Through this mechanism, drag is dependent partially upon itself.

Specifically, drag of a tree crown is more complicated by the fact that the area on which drag forces act is not known. It is expected that most drag force acting on tree crowns is eddy-type drag, hence most variation in drag coefficient of tree crowns is due to their deformation. A secondary problem arises from the fact that the center of pressure of the drag force is unknown and must be predicted as well.

Any attempt to correlate the drag on the basis of dimensionless parameters presumes linearity of the various important geometric relationships of the tree crown. A study to determine these relationships is underway.[3/]

3/ Stem and Crown Characteristics of Several Coniferous Species, report in preparation by personnel of U. S. Forest Service Division of Fire Research.

Figure 9 shows the variation of drag with velocity for a white fir seedling. The drag is linear with velocity in the range shown. This linearity is characteristic of pure laminar skin friction drag. To approach zero drag at zero velocity, however, the linear section must be preceded by a region of non-linear variation as shown by the dotted line in the figure. This agrees with qualitative results of Tiren[4] on wind-tunnel measurements of single branch drag. His results also indicate that the stiffer the branch the greater the non-linear range. If the linear variation were due to laminar drag then this laminar region must be preceded by a region of turbulent drag and a transition to laminar as the velocity increases. This is contrary to known patterns of drag variation.

Variation of drag coefficient then can only be the result of bending of the tree crown. Figures 2, 3, and 4 show degree of bending of saplings tested in the wind tunnel. Tiren indicates a further reduction of drag at higher velocity; i.e., the drag approaches a constant value. This pronounced S shape is shown by the dotted lines of Figure 9. This effect was more pronounced the more limber the branches. Results of the present study show this effect only slightly. However, velocity with respect to branch stiffness was probably not great enough.

4/ L. Tirén. "Några Undersökningar Över Stamformen." (Some Research on Tree Stem Form) Skogsvårdsföreningens Tidskrift, XXIV (Jan.-Feb. 1926), 23-88.

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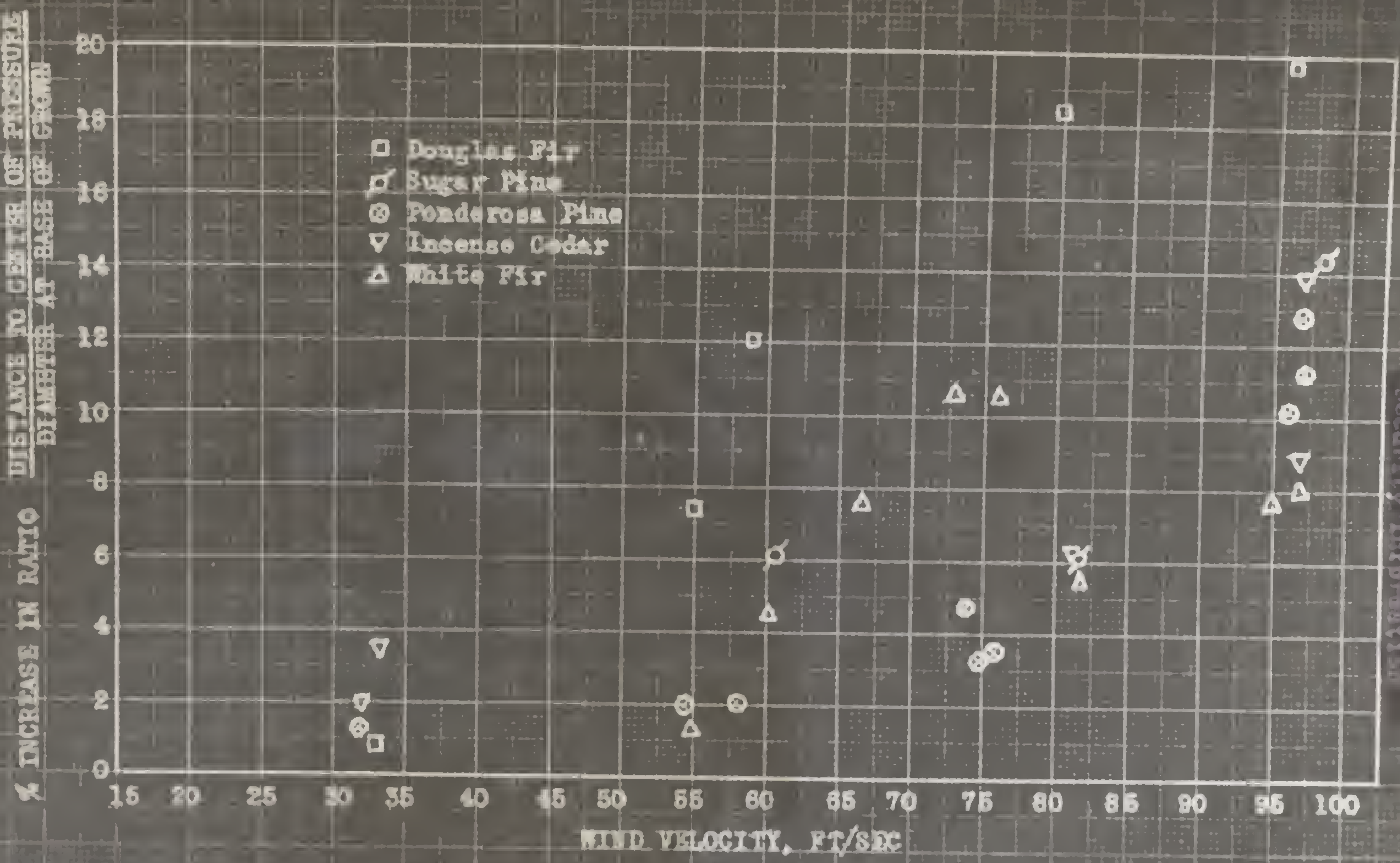

Figure 16. Variation of Location of Center of Pressure With Velocity. Wind Tunnel Measurements

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On the basis of the above discussion the correlation of data was made. The modulus of elasticity of the crowns does not appear since this remained substantially the same for all tests. However, if this property were to be changed substantially the correlation is presented would not hold. The ratio of foliage to branch weight was introduced after preliminary measurements of sapling drag indicated that foliage was the primary agent for producing drag. This is to be expected since the area-weight ratio is much greater for foliage than for branches. A crown of high foliage to branch ratio is capable of producing more drag per unit of weight of crown for the same stress to dynamic pressure ratio.

It may be noted that the data of the half-crown drag measurements for all ponderosa pine and one cedar (VT11) are not plotted. Due to the light weight of these crowns, excess vibration resulted in a large scatter of data and erroneous results.

The measured values of crown weight, height, diameter at base of crown, and other characteristics were correlated in a general manner with similar measurements made on larger tree crowns taken at the same site. These results are to be presented in a later report.5/

As noted in Figure 16 relationships presented differ for each species tested. This variation is attributed to the differing arrangement and length of needles for different species. Branch diameter to stem diameter may also be important in this respect. For the present, the data have not been analyzed to bring about convergence between species.

5/ Stem and Crown Characteristics of Several Coniferous Species, report in preparation by personnel of U. S. Forest Service Division of Fire Research.

CONCLUSIONS AND RECOMMENDATIONS

1. Variation of tree crown drag has been found to be due primarily to bending which results from the application of drag forces.

2. Data have been reduced to a set of dimensionless functional relationships which are different for each species tested; however, the general characteristics are the same.

3. Since the variation of drag with Reynolds modulus has necessarily been subjugated in this investigation, a recommendation is made to investigate the drag using a water channel.

4. The range of velocities should be extended using a sapling in order to verify further the relationships presented.